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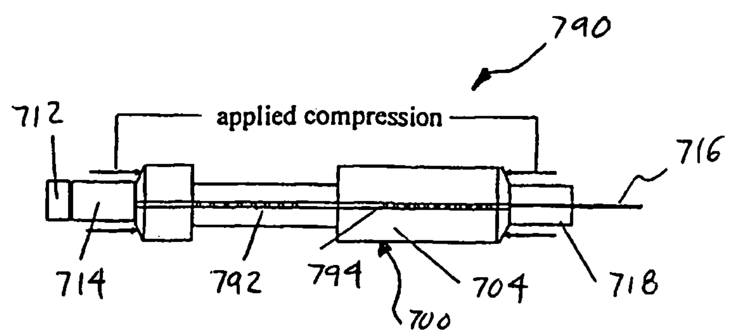
(54) Title: COMPRESSION-TUNED BRAGG GRATING-BASED LASER



(57) Abstract: A compression-tuned bragg grating-based laser includes a tunable optical element 20,600 which includes either an optical fiber 10 having at least one Bragg grating 12 impressed therein encased within and fused to at least a portion of a glass capillary tube 20 or a large diameter waveguide grating 600 having a core and a wide cladding. Light 14 is incident on the grating 12 and light 16 is reflected at a reflection wavelength $\lambda 1$. The tunable element 20,600 is axially compressed which causes a shift in the reflection wavelength of the grating 12 without buckling the element. The shape of the element may be other geometries (e.g., a"dogbone" shape) and(or more than one grating or pair of gratings may be used and more than one fiber 10 or core 612 may be used. At least a portion of the element may be doped between a pair of gratings 150,152, to form a compression-tuned laser or the grating 12 or gratings 150,152 may be constructed as a tunable DFB laser. Also, the element 20 may have an inner tapered region 22 or tapered (or fluted) sections 27. The compression may be done by a PZT, stepper motor, hydraulic device or other actuator.

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Compression-Tuned Bragg Grating-Based Laser

Cross References to Related Applications

This is a continuation-in-part of US Patent Application, Serial No. (CiDRA Docket No. CC-0129C), filed October 19, 2000, which is continuation of US Patent Application, Serial No. 09/4456,112, filed December 6, 1999, which is a continuation-in-part of US Patent Application, Serial No. 09/400,362 filed September 20, 1999, which is a continuation-in-part of US Patent Application, Serial No. 09/205,846, filed Dec. 4, 1998.

Also, copending US Patent Applications, Serial No. (CiDRA Docket No. CC-0036B), entitled "Bragg Grating Pressure Sensor", Serial No. (CiDRA Docket No. CC-0078B), entitled "Tube-Encased Fiber Grating", and Serial No. (CiDRA Docket No. CC-0230), entitled "Large Diameter Optical Waveguide, Grating and Laser" all filed December 6, 1999, and U.S. Patent Applications, Serial No. (CiDRA Docket No. CC-0254), entitled "Tunable External Cavity Semiconductor Laser Incorporating a Tunable Bragg Grating" filed November 3, 2000; US Patent Application Serial No. (CiDRA Docket No. CC-0234A), entitled "Temperature Compensated Optical Device", filed October 30,2000, and U.S. Patent Application Serial No. (CiDRA Docket No. CC-0129D), entitled "Compression-Tuned Bragg Grating-Based Laser", filed contemporaneously herewith, contains subject matter related to that disclosed herein, and which are incorporated by reference in its entirety.

Technical Field

This invention relates to tunable lasers, and more particularly to a compression-tuned Bragg grating-based laser.

Background Art

It is known in the art of fiber optics that Bragg gratings embedded in the fiber may be used in compression to act as a tunable filter or tunable fiber laser, as is described in US Patent No. 5,469,520, entitled "Compression Tuned Fiber Grating" to Morey, et al and US Patent No. 5,691,999, entitled "Compression Tuned Fiber Laser" to Ball et al..

To avoid fiber buckling under compression, the technique described in the aforementioned US Patent Nos. 5,469,520 and 5,691,999 uses sliding ferrules around the

fiber and grating and places the ferrules in a mechanical structure to guide, align and confine the ferrules and the fiber. However, it would be desirable to obtain a configuration that allows a fiber grating to be compressed without buckling and without sliding ferrules and without requiring such a mechanical structure.

Also, it is known to attach an optical fiber grating to within a glass tube to avoid buckling under compression for providing a wavelength-stable temperature compensated fiber Bragg grating as is described in US Patent No. 5,042,898, entitled "Incorporated Bragg Filter Temperature Compensated Optical Waveguide Device", to Morey et al. However, such a technique exhibits creep between the fiber and the tube over time, or at high temperatures, or over large compression ranges.

The very narrow linewidth (<10kHz) of single mode fiber lasers will, depending on the application, be an advantage (low phase noise) or a disadvantage (high power and narrow linewidth causes stimulated Brillouin scattering and hence loss). In telecom this should not be a problem since the lasers will be modulated, creating side-bands and hence effectively broadening the spectrum and increasing the threshold for Brillouin scattering.

Several fiber lasers in series or in parallel can be pumped using one semiconductor pump laser reducing the cost per fiber laser. Alternatively, parallel fiber lasers can be pumped by several pumps through a series of cross-connected couplers to form a pump redundancy scheme. With Er-lasers the pump absorption is very low and hence effectively broadening the spectrum and increasing the threshold for Brillion scattering.

Several fiber lasers in series or in parallel can be pumped using one semiconductor pump laser, reducing the cost per fiber laser. Alternatively, parallel fiber lasers can be pumped by several pumps through a series of cross-connected couplers to forma pump redundancy scheme. With Er-lasers the pump absorption is very low and hence the output power is low (~0.1mW). This can be enhanced by a MOPA design using the residual pump power to pump an EDFA. Using Er:Yb and 980nm pumping the pump absorption is greatly enhanced and the output power increased (~10mW) [Kringlebotn et al., "Efficient Diode-Pumped Single-Frequency Erbium: Ytterbium Fiber Laser", IEEE Photonics Techn. Lett, Vol. 5, No. 10, pp 1162-1164 (October 1993); and J.T. Kringlebotn et al., "Highly-efficient, Low-noise Grating-feedback Er^{3+}:TB^{3+} Codoped Fibre Laser", Eectr. Lettr., Vol. 30, No. 12, pp. 972-973, (June 1994), which are incorporated herein by reference in their entirety]. This high pump absorption can in some cases cause thermal effects resulting in mode-

hopping and power saturation. Highly photosensitive Er:Yb fibers are harder to make than Er fibers.

Various tunable semiconductor lasers have been realized. DFB lasers have a limited temperature tenability (1-2nm). Using sampled grating DBR cavities or combination of narrowband sampled grating filtering and broadband co directional filtering (using forward coupling between two parallel waveguides wide tuning ranges (->40-100nm) with relatively stable single mode operation can be realized (cf. Altitium laser). A problem with such designs is that they typically require 4 section cavities (gain, coupler, phase, reflector) with three individually/relatively controlled currents, making relatively complex and long lasers. Note that there are also various ways to make multi-wavelength/wavelength selective semiconductor laser arrays.

There are (at least) three possible FBG based single mode tunable fiber laser configurations: I) DFB, ii) DBR, and iii) sampled DBR.

DFB lasers using one phase-shifted FBG co-located with the gain medium should offer the best performance in terms of robust single mode operation, but require a highly photosensitive, high gain fiber, either Er or Er:Yb, and a relatively sophisticated FBG writing setup. DFB lasers should be able to provide the shortest grating based lasers. DBR lasers consisting of two FBG end-reflectors can be easier to realize, since separate gain fibers and grating fibers can be used (this requires low loss splicing), and the grating specs are relaxed. Mode-hopping can be a problem with DBR lasers.

Both DFB and DBR fiber lasers are continuously tunable through uniform strain of the whole cavity, including the gratings, in which case the cavity mode(s) and the Bragg wavelength are tuned equally [G. Ball and W.W. Morey, Opt. Lett., Vol. 17, pp. 420-422]. A practical tuning range in the order of 10nm should be feasible. Both DFB and DBR fiber lasers can be designed to operate in a single polarization.

A sample grating DBR uses two sampled grating end-reflectors with comb-like reflection spectra over a wide wavelength range, and where the two gratings have different comb period. Using the Vernier effect this provides wide step-wise tuning with less compression/strain than required than for DFB/DBR lasers to get the same tuning range (a reduction by a factor of 10 probably have to be quite long (several cm) to get sufficiently strong reflection from each peak.

A fiber laser can be designed to achieve single longitudinal mode lasing, as is discussed in US Patent No. 5,305,335, entitled "Single Longitudinal Mode Pumped Optical

Waveguide laser Arrangement", US Patent No. 5,317,576, entitled "Continuously Tunable Single-Mode Rare-Earth Doped Pumped Laser Arrangement", and US Patent No. 5,237,576, entitled "Article Comprising an Optical Fiber Laser", which are incorporated herein by reference in their entirety.

A general fiber laser and amplifier arrangement similar to a Master Oscillator Power Amplifier (MOPA) arrangement is described in US Patent No. 5,594,747 entitled "Dual-Wavelength Pumped Low Noise Fiber Laser", and US Patent No. 5,666,372 entitled "Embedded Bragg Grating Laser Master-Oscillator And Power-Amplifier", which are incorporated herein by reference.

Summary of the Invention

Objects of the present invention include a tunable Bragg grating-based laser that allows the grating to be compression-tuned without creep and without requiring sliding ferrules or a mechanical supporting structure for the ferrules.

According to the present invention, a compression-tuned laser comprises a tunable optical waveguide having an outer dimension of at least 0.3 mm. The optical waveguide includes an inner core disposed along the longitudinal axis of the optical waveguide. The inner core includes a dopant to provide an optical gain, and a first and second sampled grating disposed within the core along the longitudinal axis. The first and second sampled gratings are spaced a distance apart. The outer dimension of the optical waveguide about the first sample grating is different than the outer dimension of the optical waveguide about the second sample grating.

According further to the present invention, a compression-tuned laser comprises a first optical waveguide having an outer dimension of at least 0.3 mm. The first optical waveguide includes an inner core disposed along the longitudinal axis of the first optical waveguide, and a first sampled grating disposed within the core along the longitudinal axis. A second optical waveguide includes an inner core disposed along the longitudinal axis of the second optical waveguide, and a second sampled grating disposed within the core along the longitudinal axis. A gain element optically is disposed between the first and second optical waveguide. At least the first optical waveguide is compression-tunable.

The foregoing and other objects, features and advantages of the present invention will become more apparent in light of the following detailed description of exemplary embodiments thereof.

Brief Description of the Drawings

Fig. 1 is a side view of a device for compressing a tube-encased fiber grating, in accordance with the present invention.

Fig. 2 is a side view of an alternative device for compressing a tube-encased fiber grating, in accordance with the present invention.

Fig. 3 is a side view of an alternative device for compressing a tube-encased fiber grating, in accordance with the present invention.

Fig. 4 is a side view of a tube-encased fiber grating, in accordance with the present invention.

Fig. 5 is a side view of a tube-encased fiber grating having an alternative geometry for the tube, in accordance with the present invention.

Fig. 6 is a side view of a tube-encased fiber grating having an alternative geometry for the tube, in accordance with the present invention.

Fig. 7 is a side view of a tube-encased fiber grating where the tube is fused on opposite axial ends of the grating area, in accordance with the present invention.

Fig. 8 is a side view of more than one grating on a fiber encased in a tube, in accordance with the present invention.

Fig. 9 is a side view of two fiber gratings on two separate optical fibers encased in a common tube, in accordance with the present invention.

Fig. 10 is an end view of the embodiment of Fig. 9, in accordance with the present invention.

Fig. 11 is an end view of two fiber gratings on two separate optical fibers encased in a common tube and separated by distance, in accordance with the present invention.

Fig. 12 is a side view of a tube-encased fiber grating where the tube is fused on the fiber only over the length of the grating, in accordance with the present invention.

Fig. 13 is a side view of a tunable distributed feedback (DFB) fiber laser encased in a tube, in accordance with the present invention.

Fig. 14 is a side view of a device for compressing a tube-encased fiber grating using an actuator to tune the grating, in accordance with the present invention.

Fig. 15 is a side view of a device for compressing a tube-encased fiber grating using a precise pressure source to tune the grating, in accordance with the present invention.

Fig. 16 is a side view of a device for compressing a tube-encased fiber grating using a precise pressure source to tune the grating, in accordance with the present invention.

Fig. 17 is a side view of a large diameter optical waveguide having a grating disposed therein, in accordance with the present invention.

Fig. 18 is a side view of a tunable Bragg grating-based laser, in accordance with the present invention.

Fig. 19 is a side view of another embodiment of a tunable Bragg grating-based laser, in accordance with the present invention.

Fig. 20 is a side view of a temperature compensated Bragg grating-based laser, in accordance with the present invention.

Fig. 21 is a side view of another embodiment of a tunable Bragg grating-based laser having a $LiNbO_3$ electro-optic Mach-Zehnder waveguide modulator, in accordance with the present invention.

Fig. 22 is a side view of a tunable Bragg grating-based Master Oscillator Power Amplifier (MOPA), in accordance with the present invention.

Fig. 23 is a side view of a plurality of Bragg grating based laser coupled in series, in accordance with the present invention.

Fig. 24 is a side view of a sampled grating DBR laser, in accordance with the present invention.

Fig. 25 is a side view of another embodiment of a sampled grating DBR laser in accordance with the present invention.

Best Mode for Carrying Out the Invention

Referring to Fig. 1, a compression-tuned Bragg grating comprises a known optical waveguide 10, e.g., a standard telecommunication single mode optical fiber, having a Bragg grating 12 impressed (or embedded or imprinted) in the fiber 10. The fiber 10 has an outer diameter of about 125 microns and comprises silica glass (SiO_2) having the appropriate dopants, as is known, to allow light 14 to propagate along the fiber 10. The Bragg grating 12, as is known, is a periodic or aperiodic variation in the effective refractive index and/or effective optical absorption coefficient of an optical waveguide. However, any wavelength-tunable grating or reflective element embedded, etched, imprinted, or otherwise formed in the fiber 28 may be used if desired. As used herein, the term "grating" means any of such

reflective elements. Further, the reflective element (or grating) 12 may be used in reflection and/or transmission of light.

Other materials and dimensions for the optical fiber or waveguide 10 may be used if desired. For example, the fiber 10 may be made of any glass, e.g., silica, phosphate glass, or other glasses, or made of glass and plastic, or solely plastic. For high temperature applications, optical fiber made of a glass material is desirable. Also, the fiber 10 may have an outer diameter of 80 microns or other diameters. Further, instead of an optical fiber, any optical waveguide may be used, such as, a multi-mode, birefringent, polarization maintaining, polarizing, multi-core, or multi-cladding optical waveguide, or a flat or planar waveguide (where the waveguide is rectangular shaped), or other waveguides.

The light 14 is incident on the grating12 which reflects a portion thereof as indicated by a line 16 having a predetermined wavelength band of light centered at a reflection wavelength λb, and passes the remaining wavelengths of the incident light 14 (within a predetermined wavelength range), as indicated by a line 18.

The fiber 10 with the grating 12 therein is encased within and fused to at least a portion of a cylindrical glass capillary tube 20, discussed more hereinafter. The tube 20 is axially compressed by a compressing device or housing 50. One end of the tube 20 is pressed against a seat 51 in an end 52 of the housing 50. The housing 50 also has a pair of arms (or sides) 54, which guide a movable block 56. The block 56 has a seat 57 that presses against the other end of the tube 20. The end 52 and the block 56 have a hole 58 drilled through them to allow the fiber 10 to pass through. An actuator 60, such as a stepper motor or other type of motor whose rotation or position can be controlled, is connected by a mechanical linkage 62, e.g., a screw drive, linear actuator, gears, and/or a cam, to the movable block 56 (or piston) which causes the block 56 to move as indicated by arrows 64. Accordingly, the stepper motor 60 can set a predetermined amount of force on the block to compress the tube 20 to provide a desired reflection wavelength of the grating 12. Instead of the recessed seats 51,57, the tube 20 may contact the ends 52,56 with a flush contact. The stepper motor 60 may be a high resolution stepper motor driven in a microstepping mode. Other higher or lower resolution stepper motors may be used if desired. The stepper motor 60 is driven by a control circuit 63 which provides drive signals on lines 61 needed to drive the stepper motor 60, and hence the block 56, to the desired position, to provide the desired Bragg wavelength λb of the grating 12. Instead of a stepper motor, other actuators may be used if desired, as discussed hereinafter with Fig. 14.

Referring to Fig. 2, instead of using the movable block 56, a housing 70 may be used which has two end caps 72,74 and outside walls 76. In that case, the holes 58 are in the end caps 72,74 to allow the fiber 10 to exit. The stepper motor 62 is connected to the end cap 74 by the mechanical linkage 62. When the stepper motor 62 pushes on the end cap 74, the walls 76 compress or deflect, the tube 20 is compressed and the reflection wavelength of the grating 12 shifts.

Referring to Fig. 3, another embodiment of the present invention, comprises a cylindrical-shaped housing 90 comprising an outer cylindrical wall 98, two end caps 95, and two inner cylinders (or pistons) 92 each connected at one end to one of the end caps 95. The tube 20 (with the grating 12 encased therein) is disposed against the other ends of and between the two pistons 92. Other cross-sectional and/or side-view sectional shapes may be used for the housing 90 elements 98,95,92 if desired. The end caps 95 may be separate pieces or part of and contiguous with the pistons 92 and/or the outer cylinder 98.

The stepper motor 60 applies an external axial force on the end cap 95 on the left side of the housing 90. The pistons 92 have holes 94 having a diameter large enough to allow the fiber 10 pass through.

Between the inside dimension of the walls 98 and the outside dimension of tube 20 and pistons 92 is an inner I-shaped chamber 100. The pistons 92, the outer cylinder walls 98, the end caps 95, and the tube 20 may be made of the same or different materials.

An example of some possible dimensions for the housing 90 are as follows. Other dimensions may be used. The tube 20 has the outer diameter d2 of about 2 mm (0.07 inches) and a length L1 of about 12.5 mm (0.5 in.), the pistons 92 each have outer diameters d5 of about 19.1 mm (0.75 inches), the length L5 of each of the pistons 92 is about 6.25 cm (2.5 in.), the diameter of the holes 94 in the pistons 92 is about 1 mm (1000 microns), the overall length L4 of the housing 90 is about 12.7 cm (5 inches), the thickness t1 of the outside walls 98 is about 1.0 mm (0.04 inches), and the gap g1 between the inner dimension of the outer walls 98 and the outer dimensions of the pistons 92 is about 1.52 mm (0.06 inches).

The dimensions, materials, and material properties (e.g., Poisson's ratio, Young's Modulus, Coefficient of Thermal Expansion, and other known properties), of the walls 98 and the pistons 92 are selected such that the desired strain is delivered to the capillary tube 20 at an external force. The resolution and range for setting the reflection wavelength are

scalable by controlling these parameters. For example, if the overall length L4 is increased, the sensitivity ΔL/L will increase.

In particular, as the axial force from the stepper motor increases, the axial length L4 of the housing 90 decreases by an amount ΔL due to compression and/or deflection of the outer walls 98. A predetermined portion of the total axial length change ΔL' is seen at the tube 20 due to compression of the tube 20. Compression of the tube 20 lowers the Bragg reflection wavelength λ1 of the grating 12 by a predetermined amount which provides a wavelength shift. If the pistons 92 have a spring constant higher than that of the glass tube 20, the tube 20 will be compressed more than the pistons 92 for a given force. Also, for a given external force, a predetermined amount of the force is dropped across the outside walls 98, and the remainder is seen by the tube 20.

For example, when the walls 98, pistons 92 and end caps 95 are all made of titanium having the dimensions discussed hereinbefore, for an external force of 2200 lbf, about 2000 lbf is dropped across (or used to compress/deflect) the outside walls 98, and about 200 lbf is dropped across the tube 20. The cylinder walls 98 act similar to a diaphragm or bellows which compress or deflect due to increased external pressure.

The housing 90 may be assembled such that a pre-strain or no pre-stain exists on the tube 20 prior to applying any outside forces.

The material of the housings 50,70, 90 and/or one or more of the components thereof, may be made of a metal such as titanium, high nickel content alloys such as Inconel®, Incoloy®, Nimonic® (registered trademarks of Inco Alloys International, Inc.) containing various levels of Nickel, Carbon, Chromium, Iron, Molybdenum, and Titanium, stainless steel, a glass material (such as discussed hereinafter for the tube 20), or other high strength, or corrosion resistant, or high temperature or heat resistant metals or alloys may be used, or other materials having sufficient strength to compress the tube 20 may be used. Other materials having other properties may be used if desired depending on the application.

Referring to Fig. 14, alternatively, instead of using a stepper motor as the actuator, the tube 20 may be compressed by another actuator 154, such as a peizoelectric actuator, solenoid, pneumatic force actuator, or any other device which is capable of directly or indirectly applying an axial compressive force on the tube 20 may be used. The actuator 154 may be disposed on a housing 150 (analogous to the frame 50; Fig. 1) and creates a force on

a movable block 152 (analogous to the movable block 56; Fig. 1) which moves in the direction of the arrows 155.

One end of the tube 20 is pressed against the seat 51 in an end 153 of the housing 150. The housing 150 also has a pair of sides 157 which guide the movable block 152. One of the sides 157 may be removed if desired. The block 152 has the seat 57 that presses against the other end of the tube 20.

Also, the actuator 154 is connected to a control circuit 158 which provides the necessary signals on a line 156 to the actuator 154 to set the desired force on the tube 20 which sets the desired Bragg wavelength λb of the grating 12. The force may be set by the controller 158 by providing a signal (e.g., an electrical voltage) on the line 156 to the actuator 154 in an open loop configuration. Alternatively, the force may be set on the actuator 154 by providing a signal on the line 156 to the actuator 154 and measuring the force or position of the actuator 154 on a line 160 in a closed loop control configuration on the actuator 154.

For single ended operation, the fiber 10 may enter on one end of the housing 150 and pass through a hole 162 in the end 153. If a feed-through (double ended fiber) design is used, the block 152 may have a hole 164 part or all the way through it, and the other end of the fiber 10 may be fed out the side or passed through a hole 166 in the actuator 154 and in the other end of the housing 150.

One example of a closed loop piezoelectric actuator that may be used is Model No. CM (controller) and DPT-C-M (for a cylindrical actuator) made by Queensgate, Inc. of N.Y. Other actuators may be used, as discussed hereinbefore.

Referring to Fig. 15, alternatively, the tube 20 may be placed in a housing 174, and the grating wavelength set by placing a fluid pressure on the tube 20, similar to a pressure sensor described in co-pending US Patent Application, Serial No. 09/205,944 entitled "Tube-Encased Fiber Grating Pressure Sensor", filed Dec. 4, 1998, which is incorporated herein by reference, and the tube 20 may have any of the geometries and configurations described in such Patent Application. The housing 172 creates a chamber 176 and has a port 178 that is fed to a pressure source 180, which provides a precise source pressure Ps. The chamber 176 may be filled with a fluid (e.g., one or more gasses and/or liquids). The tube 20 may be mounted to one wall 175 or may be suspended in the fluid 176. The optical fiber 10 is fed into the chamber through a known hermetic feedthroughs and has some slack 179 to allow for compression of the tube 20 over pressure. The grating reflection wavelength

changes as the pressure Ps changes, similar to the actuator embodiments discussed hereinbefore; however, in this case, the grating wavelength is set by setting a predetermined source fluid pressure Ps.

Referring to Fig. 16, for example, the pressure source 180 may comprise a hydraulic actuator or piston 300 disposed within a chamber 301. The piston 300 is connected by a mechanical linkage 302 to a known hydraulic drive mechanism 304 which precisely sets the position of the piston 300 to set the pressure Ps. The hydraulic drive 304 may be controlled electronically by a known control circuit 308, similar to the controller 158 (Fig. 14), which provides a position command signal on a line 306 to the hydraulic controller 304 for a particular piston position and thus pressure Ps, and thus wavelength λb of the grating. Other known pressure sources may be used if desired to set the grating wavelength. The housings described herein 50,150,70,90, and any components therein, including the movable blocks 56,152, may have a circular cross-section (i.e., cylindrical shape) or may have other cross-sectional shapes, such as square, rectangular, or other shapes.

Although the invention has been described with some specific embodiments with Figs. 1-3,14,15 for compressing the tube 20, any device or fixture, which compresses the tube axially may be used for compressing the tube 20 to tune the reflection wavelength of the grating 12 to the desired wavelengths. The exact hardware configuration is not critical to the present invention.

For any of the embodiments described herein, the axial end faces of the tube 20 and/or the seats on mating surfaces (56,50,92,74,72,153,159) may be plated with a material that reduces stresses or enhances the mating of the tube 20 with the seat on the mating surfaces. Referring to Fig. 4, the tube 20 may have an outer diameter d1 of about 3 mm and a length L1 of about 10-30 mm. The grating 12 has a length Lg of about 5-15 mm. Alternatively, the length L1 of the tube 20 may be substantially the same length as the length Lg of the grating 12, such as by the use of a longer grating, or a shorter tube. Other dimensions and lengths for the tube 20 and the grating 12 may be used. Also, the fiber 10 and grating 12 need not be fused in the center of the tube 20 but may be fused anywhere in the tube 20. Also, the tube 20 need not be fused to the fiber 10 over the entire length of the tube 20.

The dimensions and geometries for any of the embodiments described herein are merely for illustrative purposes and, as such, any other dimensions may be used if desired,

depending on the application, size, performance, manufacturing requirements, or other factors, in view of the teachings herein.

The tube 20 is made of a glass material, such as natural or synthetic quartz, fused silica, silica (SiO_2), Pyrex® by Corning (boro silicate), or Vycor® by Corning Inc. (about 95% silica and 5% other constituents such as Boron Oxide), or other glasses. The tube should be made of a material such that the tube 20 (or the inner diameter surface of a bore hole in the tube 20) can be fused to (i.e., create a molecular bond with, or melt together with) the outer surface (or cladding) of the optical fiber 10 such that the interface surface between the inner diameter of the tube 20 and the outer diameter of the fiber 10 become substantially eliminated (i.e., the inner diameter of the tube 20 cannot be distinguished from and becomes part of the cladding of the fiber 10).

For best thermal expansion matching of the tube 20 to the fiber 10 over a large temperature range, the coefficient of thermal expansion (CTE) of the material of the tube 20 should substantially match the CTE of the material of the fiber 10, e.g., fused silica tube and optical fiber. In general, the lower the melting temperature of the glass material, the higher the CTE. Thus, for a silica fiber (having a high melting temperature and low CTE) and a tube made of another glass material, such as Pyrex® or Vycor® (having a lower melting temperature and higher CTE) results in a thermal expansion mismatch between the tube 20 and the fiber 10 over temperature. However, it is not required for the present invention that the CTE of the fiber 10 match the CTE of the tube 20 (discussed more hereinafter).

Instead of the tube 20 being made of a glass material, other elastically deformable materials may be used provided the tube 20 can be fused to the fiber 10. For example, for an optical fiber made of plastic, a tube made of a plastic material may be used.

The axial ends of the tube 20 where the fiber 10 exits the tube 20 may have an inner region 22, which is inwardly tapered (or flared) away from the fiber 10 to provide strain relief for the fiber 10 or for other reasons. In that case, an area 28 between the tube 20 and the fiber 10 may be filled with a strain relief filler material, e.g., polyimide, silicone, or other materials. Also, the tube 20 may have tapered (or beveled or angled) outer corners or edges 24 to provide a seat for the tube 20 to mate with another part (not shown) and/or to adjust the force angles on the tube 20, or for other reasons. The angle of the beveled corners 24 are set to achieve the desired function. The tube 20 may have cross-sectional shapes other than circular, such as square, rectangular, elliptical, clam-shell, or other shapes,

and may have side-view sectional shapes other than rectangular, such as circular, square, elliptical, clam-shell, or other shapes.

Alternatively, instead of having the inner tapered axial region 22, one or both of the axial ends of the tube 20 where the fiber 10 exits the tube 20 may have an outer tapered (or fluted, conical, or nipple) axial section, shown as dashed lines 27, which has an outer geometry that decreases down to the fiber 10 (discussed more hereinafter with Fig. 12). We have found that using the fluted sections 27 provides enhanced pull strength at and near the interface where the fiber 10 exits the tube 20, e.g., 6 lbf or more, when the fiber 10 is pulled along its longitudinal axis.

Where the fiber 10 exits the tube 20, the fiber 10 may have an external protective buffer layer 21 to protect the outer surface of the fiber 10 from damage. The buffer 21 may be made of polyimide, silicone, Teflon® (polytetraflouroethylene), carbon, gold, and/or nickel, and have a thickness of about 25 microns. Other thicknesses and buffer materials for the buffer layer 21 may be used. If the inner tapered region 22 is used and is large enough, the buffer layer 21 may be inserted into the region 22 to provide a transition from the bare fiber to a buffered fiber. Alternatively, if the axial end of the tube 20 has the external taper 27, the buffer 21 would begin where the fiber exits the tapered 27 portion of the tube 20. If the buffer 21 starts after the fiber exit point, the exposed bare portion of the fiber 10 may be recoated with an additional buffer layer (not shown) which covers any bare fiber outside of the tube 20 and may also overlap with the buffer 21 and/or some of the tapered region 27 or other geometrically shaped axial end of the tube 20.

To encase the fiber 10 within the tube 20, the tube 20 may be heated, collapsed, and fused to the grating 12, by a laser, filament, flame, etc., as is described in copending US Patent Application, Serial No. (CiDRA Docket No. CC-0078A), entitled "Tube-Encased Fiber Grating", which is incorporated herein by reference. Other techniques may be used for collapsing and fusing the tubes 20 to the fiber 10, such as is discussed in US Patent No. 5,745,626, entitled "Method For And Encapsulation Of An Optical Fiber", to Duck et al., and/or US Patent No. 4,915,467, entitled "Method of Making Fiber Coupler Having Integral Precision Connection Wells", to Berkey, which are incorporated herein by reference to the extent necessary to understand the present invention, or other techniques. Alternatively, other techniques may be used to fuse the fiber 10 to the tube 20, such as using a high temperature glass solder, e.g., a silica solder (powder or solid), such that the fiber 10, the tube 20 and the solder all become fused to each other, or using laser welding/fusing or other

fusing techniques. Also, the fiber may be fused within the tube or partially within or on the outer surface of the tube (discussed hereinafter with Fig. 11).

The Bragg grating 12 may be impressed in the fiber 10 before or after the capillary tube 20 is encased around and fused to the fiber 10, such as is discussed in copending US Patent Application, Serial No. (CiDRA Docket No. CC-0078), which is incorporated herein by reference. If the grating 12 is impressed in the fiber 10 after the tube 20 is encased around the grating 12, the grating 12 may be written through the tube 20 into the fiber 10 by any desired technique, such as is described in copending US Patent Application, Serial No. 09/205,845 (CiDRA Docket No. CC-0130), entitled "Method and Apparatus For Forming A Tube-Encased Bragg Grating", filed December 4, 1998.

The grating 12 may be encased in the tube 20 having an initial pre-strain from the tube (compression or tension) or no pre-strain. For example, if Pyrex® or another glass that has a larger coefficient of thermal expansion (CTE) than that of the fiber 10 is used for the tube 20, when the tube 20 is heated and fused to the fiber and then cooled, the grating 12 is put in compression by the tube 20. Alternatively, the fiber grating 12 may be encased in the tube 20 in tension by putting the grating in tension during the tube heating and fusing process. In that case, when the tube 20 is compressed, the tension on the grating 12 is reduced. Also, the fiber grating 12 may be encased in the tube 20 resulting in neither tension nor compression on the grating 12 when no external forces are applied to the tube 20.

Referring to Fig. 5, the capillary tube 20 may have a varying geometry, depending on the application. For example, the tube 20 may have a "dogbone" shape having a narrow central section 30 and larger outer sections 32. The narrow section 30 has an outer diameter d2 of about 1 mm, and a length L2 of about 5 mm. The large sections 32 each have a diameter d3 of about 3 mm and a length L3 of about 4 mm. Other lengths and diameters of the sections 30,32 may be used. The dogbone shape may be used to provide increased sensitivity in converting force applied by the stepper motor 60 or actuator 154 to wavelength shift of the tube-encased grating 12.

An inner transition region 33 of the large sections 32 may be a sharp vertical or angled edge or may be curved as indicated by dashed lines 34. A curved geometry 34 has less stress risers than a sharp edge and thus may reduce the likelihood of breakage. Also, the sections 32 of the tube 20 may have the inner tapered regions 22 or the outer fluted sections 27 at the ends of the tube 20, as discussed hereinbefore. Further, the sections 32 may have the tapered (or beveled) outer corners 24 as discussed hereinbefore.

Also, it is not required that the dogbone geometry be symmetric, e.g., the lengths L3 of the two sections 32 may be different if desired. Alternatively, the dogbone may be a single-sided dogbone, where instead of the having the two larger sections 32, there may be only large section 32 on one side of the narrow section 30 and the other side may have a straight edge 37 which may have beveled corners 24 as discussed hereinbefore. In that case, the dogbone has the shape of a "T" on its side. Such a single-sided dogbone shall also be referred to herein as a "dogbone" shape. Instead of a dogbone geometry, other geometries that provide enhanced strain sensitivity or adjust force angles on the tube 20 or provide other desirable characteristics may be used.

We have found that such a dimension change between the dimension d3 of the large section 32 and the dimension d2 of the narrow section 30 provides increased force to grating wavelength shift sensitivity (or gain or scale factor) by strain amplification. Also, the dimensions provided herein for the dogbone are easily scalable to provide the desired amount of sensitivity.

Referring to Fig. 6, alternatively, to help reduce strain on the fiber 10 at the interface between the fiber 10 and the tube 20, the tube 20 may have sections 36 which extend axially along the fiber 10 and attach to the fiber 10 at a location that is axially outside where the force is applied on the large sections 32 by opposing end pieces 104,105, which are equivalent to the end pieces 56,50 (Fig. 1), 74,72 (Fig. 2), 159,153 (Fig. 14), respectively, or the pistons 92 (Fig. 3). The axial length of the sections 36 may be about 20 mm; however, longer or shorter lengths may be used depending on the application or design requirements. Also, the sections 36 need not be axially symmetrical, and need not be on both axial ends of the tube 20. The sections 32 may have the inner tapered regions 22 or the outer fluted sections 27 where the fiber interfaces with the tube 20, as discussed hereinbefore. Alternatively, there may be a stepped section 39 as part of the sections 36. In that case, the region 22 may be within or near to the stepped section 39 as indicated by dashed lines 38. The regions 106 may be air or filled with an adhesive or filler. Also, the tube 20 may have a straight constant cross-section as discussed hereinbefore and as indicated by the dashed lines 107 instead of a dogbone shape. Further, the hole 108 through the end pieces 56,50 (Fig. 1), 74,72 (Fig. 2), 152,150 (Fig. 14), respectively, or the pistons 92 (Fig. 3) may have a larger diameter as indicated by the dashed lines 109 for all or a portion of the length of the hole 108.The capillary tube 20 may have other axial extending geometries, such as is discussed in the aforementioned copending US Patent Application,

Serial No. (CiDRA Docket No. CC-0078B). Also, more than one concentric tube may be used to form the tube 20 of the present invention, as discussed in the aforementioned copending US Patent Application. Also, the axially extended sections 36 may be part of an inner tube.

Referring to Fig. 7, alternatively, the tube 20 may be fused to the fiber 10 on opposite sides of the grating 12. In particular, regions 200 of the tube 20 are fused to the fiber 10 and a central section 202 of the tube around the grating 12 is not fused to the fiber 10. The region 202 around the grating 12 may contain ambient air or be evacuated (or be at another pressure) or may be partially or totally filled with an adhesive, e.g., epoxy, or other filling material, e.g., a polymer or silicone, or another material or may be not filled. As discussed hereinbefore, the inner diameter d6 of the tube 20 is about 0.01 to 10 microns larger than the diameter of the optical fiber 10, e.g., 125.01 to 135 microns. Other diameters may be used; however, to help avoid fiber buckling in this embodiment, the diameter d6 should be as close as possible to the fiber 10 outer diameter. Alternatively, the same result can be achieved by fusing two separate tubes on opposite sides of the grating 12 and then fusing an outer tube across the tubes, as discussed in the aforementioned copending US Patent Application.

We have found that the present invention provides high repeatability, low creep and low hysteresis (e.g., about 3 picometers or less), depending on the configuration used. Referring to Fig. 8, for any of the embodiments described herein, instead of a single grating encased within the tube 20, two or more gratings 220,222 may be embedded in the fiber 10 that is encased in the tube 20. The gratings 220,222 may have the same reflection wavelengths and/or profiles or different wavelengths and/or profiles. The multiple gratings 220,222 may be used individually in a known Fabry Perot arrangement.

Further, one or more fiber lasers, such as that described in US Patent No. 5,666,372, "Compression-Tuned Fiber Laser" (which is incorporated herein by reference to the extent necessary to understand the present invention) may be embedded within the fiber 10 in the tube 20 and compression-tuned. In that case, the gratings 220,222 form a cavity and the fiber 10 at least between the gratings 220,222 (and may also include the gratings 220,222, and/or the fiber 10 outside the gratings, if desired) would be doped with a rare earth dopant, e.g., erbium and/or ytterbium, etc., and the lasing wavelength would be tuned accordingly as the force on the tube 20 changes.

Referring to Fig. 13, another type of tunable fiber laser that may be used is a tunable distributed feedback (DFB) fiber laser 234, such as that described in V.C. Lauridsen, et al, "Design of DFB Fibre Lasers", Electronic Letters, Oct. 15, 1998, Vol.34, No. 21, pp 2028-2030; P. Varming, et al, "Erbium Doped Fiber DGB Laser With Permanent $\pi/2$ Phase-Shift Induced by UV Post-Processing", IOOC'95, Tech. Digest, Vol. 5, PD1-3, 1995; US Patent No. 5,771,251, "Optical Fibre Distributed Feedback Laser", to Kringlebotn et al; or US Patent No. 5,511,083, "Polarized Fiber Laser Source", to D'Amato et al., which are incorporated herein by reference in their entirety. In that case, the grating 12 is written in a rare-earth doped fiber and configured to have a phase shift of $\lambda/2$ (where λ is the lasing wavelength) at a predetermined location 224 near the center of the grating 12 which provides a well defined resonance condition that may be continuously tuned in single longitudinal mode operation without mode hopping, as is known. Alternatively, instead of a single grating, the two gratings 220,222 may be placed close enough to form a cavity having a length of $(N + ½)\lambda$, where N is an integer (including 0) and the gratings 220,222 are in rare-earth doped fiber.

Alternatively, the DFB laser 234 may be located on the fiber 10 between the pair of gratings 220,222 (Fig. 8) where the fiber 10 is doped with a rare-earth dopant along at least a portion of the distance between the gratings 220,222. Such configuration is referred to as an "interactive fiber laser", as is described by J.J. Pan et al, "Interactive Fiber Lasers with Low Noise and Controlled Output Power", E-tek Dynamics, Inc., San Jose, CA, internet web site www.e-tek.com/products/ whitepapers, which are incorporated by reference in their entirety. Other single or multiple fiber laser configurations may be disposed on the fiber 10 if desired.

Referring to Figs. 9 and 10, alternatively, two or more fibers 10,250, each having at least one grating 12,252 therein, respectively, may be encased within the tube 20. The gratings 12,252 may have the same reflection wavelengths and/or profiles or different wavelengths and/or profiles. In that case, the bore hole in the tube 20 prior to heating and fusing the tube 20 would be large enough to contain both fibers 10,250 and may be other than circular, e.g., square, triangle, etc. Also, the bore hole for the tube 20 need not be centered along the center line of the tube 20.

Referring to Fig. 11, alternatively, instead of the fibers 10,250 touching each other as shown in Fig. 10, the fibers 10,250 may be spaced apart in the tube 20 by a predetermined distance. The distance may be any desired distance between the fibers 10,250

and have any orientation within the outer diameter of the tube 20. Also, for any of the embodiments shown herein, as discussed hereinbefore, part or all of an optical fiber and/or grating may be fused within, partially within, or on the outer surface of the tube 20, as illustrated by fibers 500,502,504, respectively.

Referring to Fig. 12, alternatively, the tube 20 may be fused onto the fiber 10 only where the grating 12 is located. In that case, if the tube 20 is longer than the grating 12, the inner tapered or flared regions 22 discussed hereinbefore may exist and the areas 28 between the tube 20 and the fiber 10 may be filled with a filler material, as discussed hereinbefore. Also, the term "tube" as used herein may also mean a block of material having the properties described herein.

Further, for any of the embodiments shown herein, instead of the fiber 10 passing through the housing 50,70,90 or the tube 20, the fiber 10 may be single-ended, i.e., only one end of the fiber 10 exits the housing or the tube 20. In that case, one end of the fiber 10 would be at or prior to the exit point of the fiber 10 from the tube 20 or the housing 50,70,90.

Referring to Fig. 17, alternatively, a portion of or all of the tube-encased fiber grating 20 may be replaced by a large diameter silica waveguide grating 600, such as that described in copending US Patent Application Serial No. (CiDRA Docket No. CC-0230), entitled "Large Diameter Optical Waveguide, Grating and Laser", which is incorporated herein by reference. The waveguide 600 has a core 612 (equivalent to the core of the fiber 10) and a cladding 614 (equivalent to the fused combination of the tube 20 and the cladding of the fiber 10) and having the grating 12 embedded therein. The overall length L1 of the waveguide 600 and the waveguide diameter d2 are set the same as that described hereinbefore for the tube 20 (i.e., such that the tube 20 will not buckle over the desired grating wavelength tuning range) and the outer diameter of the waveguide is at least 0.3 mm. An optical fiber 622 (equivalent to the fiber 10 in Fig. 1) having a cladding 626 and a core 625 which propagates the light signal 14, is spliced or otherwise optically coupled to one or both axial ends 628 of the waveguide 600 using any known or yet to be developed techniques for splicing fibers or coupling light from an optical fiber into a larger waveguide, that provides acceptable optical losses for the application.

The large diameter waveguide with grating 600 may be used in the same ways as the tube encased grating 20 is used herein where the fiber 10 is analogous to (and interchangeable with) the core 612 of the waveguide 600. For example, the waveguide 600

may be etched, ground or polished to achieve the "dogbone" shape described hereinbefore with the tube 20. Alternatively, the "dogbone" shape may be obtained by heating and fusing two outer tubes 640,642 onto opposite ends of the waveguide 600.

All other alternative embodiments described herein for the tube 20 and the tube-encased grating are also applicable to the waveguide 600 where feasible, including having a fiber laser or a DFB fiber laser, multiple fibers (or cores), various geometries, etc.

The tube-encased fiber grating 20 and the large diameter waveguide grating 600 may each also be referred to herein as a "tunable optical element". The tube-encased grating 20 and the large diameter waveguide grating 600 have substantially the same composition and properties in the locations where the tube 20 is fused to the fiber 10, because the end (or transverse) cross-section of the tube-encased grating 20 and the large diameter waveguide grating 600 are contiguous (or monolithic) and made of substantially the same material across the cross-section, e.g., a glass material, such as doped and undoped silica. Also, in these locations both have an optical core and a large cladding.

Also, the waveguide 600 and the tube-encased grating 20 may be used together to form any given embodiment of the sensing element described herein. In particular, one or more axial portion(s) of the sensing element may be a tube-encased grating or fiber and/or one or more other axial portion(s) may be the waveguide 600 which are axially spliced or fused or otherwise mechanically and optically coupled together such that the core of said waveguide is aligned with the core of the fiber fused to the tube. For example, a central region of the sensing element may be the large waveguide and one or both axial ends may be the tube-encased fiber which are fused together as indicated by dashed lines 650,652, or visa versa (Figs. 1,11,31).

In the tunable grating-based laser embodiments shown in Figs. 18-25, a laser element 700 includes a laser grating(s) 702 is written in a large diameter gain waveguide (i.e., cane) 704, having a single mode core <10um diameter and doped with one or more of the rare-earths (e.g. Erbium or Erbium: Ytterbium) to provide gain, and a thick outer cladding to give the fiber an outer diameter of >300 um. The laser can either be a DFB fiber laser, where the grating is written in the core of the cane 704 (or tube-encased gain fiber), or a DBR laser, which consists of two Bragg grating end reflectors 702, either written in respective highly photosensitive cane elements (or respective tube-encased fibers) with a gain fiber spliced therebetween, or both written within a single cane element, which is formed of gain material, (or tube-encased gain fiber).

Referring to Figs. 18 and 19, a compact, inexpensive compression-tuned Bragg grating-based laser 710 includes a bulk semiconductor pump laser chip 712, launching pump light into the Bragg grating laser cavity through a micro lens 714, e.g., a GRIN lens. Alternatively, the lens 714 can be part of the cane through machining of the end of the cane 704. A fiber output pigtail 716 inside a ferrule/glass capillary 718 is glued to the glass canter with the fiber 716 aligned to the laser element 700. The Bragg grating laser cavity should be designed to emit most light out of the output end by making an asymmetric laser cavity with respect to output coupling. The pump laser 712 can be directed inside the glass cane either at the input and/or at the output of the first laser cavity. The short distance between the pump chip 712 and the stabilizing grating 702 might require an anti reflection coating at the output facet of the pump chip. Normally grating stabilized pump lasers operate in the "coherence collapse" regime with a weak grating separated by ~1m from the pump laser.

To monitor the laser power some of the laser output as shown in Fig. 19, either from the input or the output end of the laser 730, can be directed to a monitor detector 732 via a beam splitter 734. This can be used to control the output power of the laser and also to reduce the intensity noise of the laser through negative feedback to the pump.

The laser cavity inside the glass cane can be mechanically compressed to make a continuously wavelength tunable laser 730, basically using the same design, compression actuation and wavelength control as described hereinbefore. With pump reflector Bragg gratings (BGs) 736, these are disposed in a section of the glass cane 704 which is not under compression.

Referring to Fig. 20, the tunable laser 740 provides a fixed laser wavelength with a high degree of wavelength stability can be realized by putting the glass cane 704 in compression with a section of material 742 with higher thermal expansion coefficient as a part of the compressed length. The housing 744 around the compressed length should have a low thermal expansion coefficient. The high thermal expansion material 742 will with increasing temperature compress the laser cavity to counter-act the positive wavelength shift caused by the temperature dependence of the refractive index of the laser element 700.

Referring to Fig. 21, a Bragg grating laser 750 having an external modulator 752 is illustrated. Rather than using a pigtailed modulator, a bulk modulator could possibly be integrated in the fiber laser module. In this case a LiNbO3 electro-optic Mach-Zehnder waveguide modulator is aligned with the output of the laser passing a bulk optical isolator

754 put between two GRIN lenses 756,758. A dielectric pump stop filter 760 at the output of the laser is also included in this configuration.

In the case of an Erbium-only Bragg grating laser 770, the residual pump power at the output of the laser (very little pump power is absorbed in a short laser cavity) can be used to pump an EDFA 772 in a MOPA (Master Oscillator Power Amplifier) configuration, as illustrated in Fig. 22. Since an optical isolator 774 is needed between the laser and the amplifier, a 1480nm pump source is needed, where the pump light will pass an optical isolator in the 1550 nm laser band.

Alternatively, as shown in Fig. 23, the residual pump power of the laser of Fig. 22 can also be used to pump several other Bragg grating lasers 776 that are optically connected in series, having different wavelengths. These can be compression-tuned separately or together. In making such a multi-wavelength laser array 780, all lasers will laser simultaneously. With Bragg grating-based DFB lasers, the individual lasers can be turned on/off by switching the optical phase-shift inside the laser grating 702, for example by applying local heating or a local strain at 782. This will enable a wavelength selective laser array. It could also provide a widely tunable laser by tuning laser 1 at λ_1 over a certain wavelength band with all other lasers off, then letting laser 2 at λ_2 take over to tune over the adjacent wavelength band while turning laser 1 off and so forth. Changing the phase shifts can also be used to control the relative power between the lasers, for example to dynamically equalize the powers. Note that changing the phase shift will also cause a shift in laser wavelength, with an amount depending on the position of the phase shift. This can be compensated for by changing the compression/strain (or temperature) of the laser. Alternatively changes in phase-shift can be used to modulate the laser frequency.

Referring to Figs. 24 and 25, to enhance the tuning range of a grating based single frequency laser for a given compression, it is possible to make a sampled grating DBR fiber laser 790. One of the sampled gratings 792 is tuned relative to the other sampled grating 794 to provide stepwise tuning in steps equal to the spectral separation between each peak (which can be made to match the ITU grid). One possible way of doing this is to compress both gratings 702, as illustrated in Fig. 24, making the tuning sensitivity to compression different for the two gratings by writing them in sections of the glass cane 704 having different diameters. Due to the reduced grating reflectivity of each peak for a sampled grating required to make a laser, the length of the laser element 700 will probably be quite long (e.g., >10 cm).

Alternatively, one of the gratings 792 another embodiment of the laser 796 may be maintained fixed and only the second grating 794 is tuned, as illustrated in Fig. 25. The configuration has a coil of gain fiber 798 (e.g. erbium-doped fiber ("EDF")) between the gratings. Also the length of each sampled grating may be >20 mm to provide sufficient reflection over a wide wavelength range. For a relatively long cavity length, the sampled grating DBR laser may mode-hop between neighboring longitudinal cavity modes due to the small longitudinal mode-spacing relative to the bandwidth of each reflection peak. Consequently, the length of the coil of gain fiber 798 may to relatively short to reduce mode-hopping. In another embodiment (not shown), both sampled gratings 702 may be individually tunable to provide quasi-continuous tuning of the laser 796.

Further, the invention may be used with a co-doped distributed feedback laser arrangement similar to that described in the articles: J. Kringlebotn et al., "Er+3: Yb+3-Codoped Fiber Distributed-Feedback Laser", Optics Letters, Vol. 19, No. 24, pp 2101-2103 (December 1994); and H. Kogelnik et al, "Coupled-Wave Theory of Distributed Feedback Lasers", J. Appl. Phys., Vol. 43, No. 5, pp 2327-2335 (May 1972), which are incorporated herein by reference in their entirety.

It should be understood that, unless stated otherwise herein, any of the features, characteristics, alternatives or modifications described regarding a particular embodiment herein may also be applied, used, or incorporated with any other embodiment described herein. Also, the drawings herein are not drawn to scale.

Although the invention has been described and illustrated with respect to exemplary embodiments thereof, the foregoing and various other additions and omissions may be made therein and thereto without departing from the spirit and scope of the present invention.

Claims

What is claimed is:

1. A compression-tuned laser, comprising:

a tunable optical waveguide having an outer dimension of at least 0.3 mm, the optical waveguide including:

an inner core disposed along the longitudinal axis of the optical waveguide, the inner core including a dopant to provide an optical gain; and

a first and second sampled grating disposed within the core along the longitudinal axis, the first and second sampled gratings being spaced a distance apart;

wherein the outer dimension of the optical waveguide about the first sample grating is different than the outer dimension of the optical waveguide about the second sample grating.

2. The compression-tuned laser of claim 1, wherein only one grating of the first sampled grating aligns optically with one grating of the second sampled grating over the desired tuning range.

3. The compression-tuned laser of claim 1, wherein the center wavelengths of the gratings of the first and second sampled gratings are spaced to provide stepwise tuning in steps equal to the spectral separation of the center wavelengths.

4. The compression-tuned laser of claim 3, wherein the steps match the ITU grid.

5. The compression-tuned laser of claim 1 wherein said tunable optical waveguide comprises:

an optical fiber, having the first and second sampled gratings embedded therein; and

a tube, having said optical fiber and the first and second sampled gratings encased therein along a longitudinal axis of said tube, said tube being fused to at least a portion of said fiber.

6. The compression-tuned laser of claim 1 wherein said tunable element comprises a large diameter optical waveguide having an outer cladding and the inner core disposed therein.

7. The compression-tuned laser of claim 1, wherein dopant is a rare-earth dopant.

8. The compression-tuned laser of claim 1 wherein at least a portion of said tunable optical waveguide comprises a cylindrical shape.

9. A compression-tuned laser, comprising:

a first optical waveguide having an outer dimension of at least 0.3 mm, the first optical waveguide including:

an inner core disposed along the longitudinal axis of the first optical waveguide; and

a first sampled grating disposed within the core along the longitudinal axis; and

a second optical waveguide including:

an inner core disposed along the longitudinal axis of the second optical waveguide; and

a second sampled grating disposed within the core along the longitudinal axis; and

a gain element optically disposed between the first and second optical waveguide; wherein at least the first optical waveguide is compression-tunable.

10. The compression-tuned laser of claim 9, wherein the second optical waveguide has an outer dimension of at least 0.3 mm.

11. The compression-tuned laser of claim 10, wherein both the first and second optical waveguides are tunable.

12. The compression-tuned laser of claim 9, wherein sampled grating of the second optical waveguide is fixed.

13. The compression-tuned laser of claim 12, wherein the second optical waveguide has an outer dimension of at least 0.3 mm.

14. The compression-tuned laser of claim 12, wherein the second optical waveguide is an optical fiber.

15. The compression-tuned laser of claim 9, wherein only one grating of the first sampled grating aligns optically with one grating of the second sampled grating over the desired tuning range.

16. The compression-tuned laser of claim 9, wherein the center wavelengths of the gratings of the first and second sampled gratings are spaced to provide stepwise tuning in steps equal to the spectral separation of the center wavelengths.

17. The compression-tuned laser of claim 16, wherein the steps match the ITU grid.

18. The compression-tuned laser of claim 9 wherein at least one of the first and second tunable optical waveguides comprises:

an optical fiber, having the first and second sampled gratings embedded therein; and

a tube, having said optical fiber and the first and second sampled gratings encased therein along a longitudinal axis of said tube, said tube being fused to at least a portion of said fiber.

19. The compression-tuned laser of claim 9 wherein at least one of the first and second tunable optical waveguides comprises a large diameter optical waveguide having an outer cladding and the inner core disposed therein.

20. The compression-tuned laser of claim 9, wherein gain element comprises a doped fiber.

21. The compression-tuned laser of claim 9, wherein gain element comprises an erbium-doped fiber.

22. The compression-tuned laser of claim 9 wherein at least a portion of the first tunable optical waveguide comprises a cylindrical shape.

23. The compression-tuned laser of claim 9 wherein the first tunable optical waveguide comprises a shape that provides a predetermined sensitivity to a shift in said wavelength due to a change in force on the first tunable optical waveguide.

24. The compression-tuned laser of claim 22 wherein said shape of the first tunable optical waveguide comprises a dogbone shape.

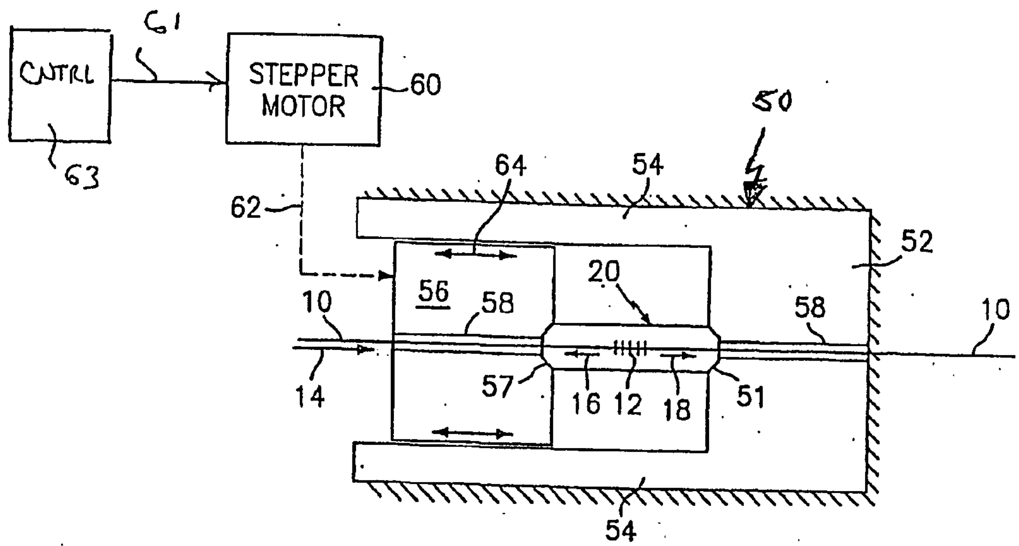


FIG. 1

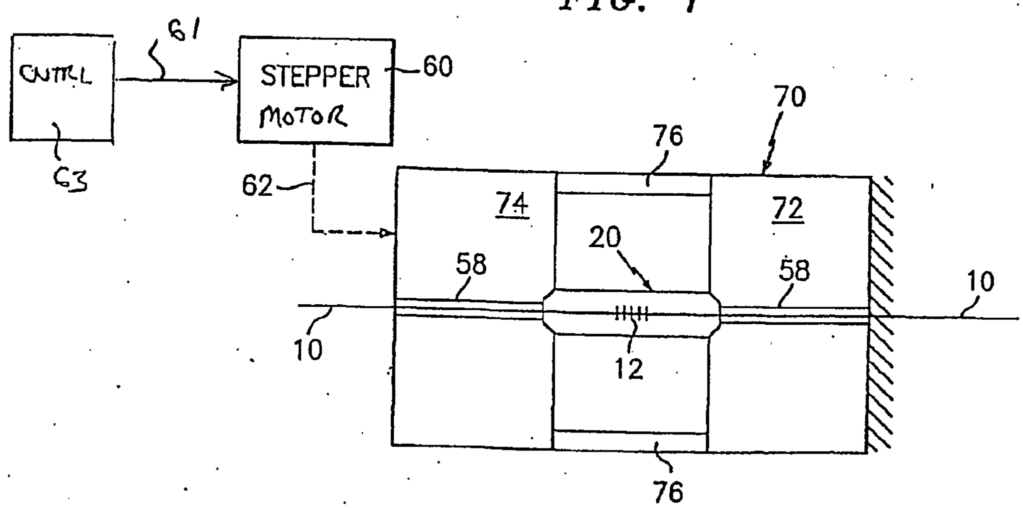


FIG. 2

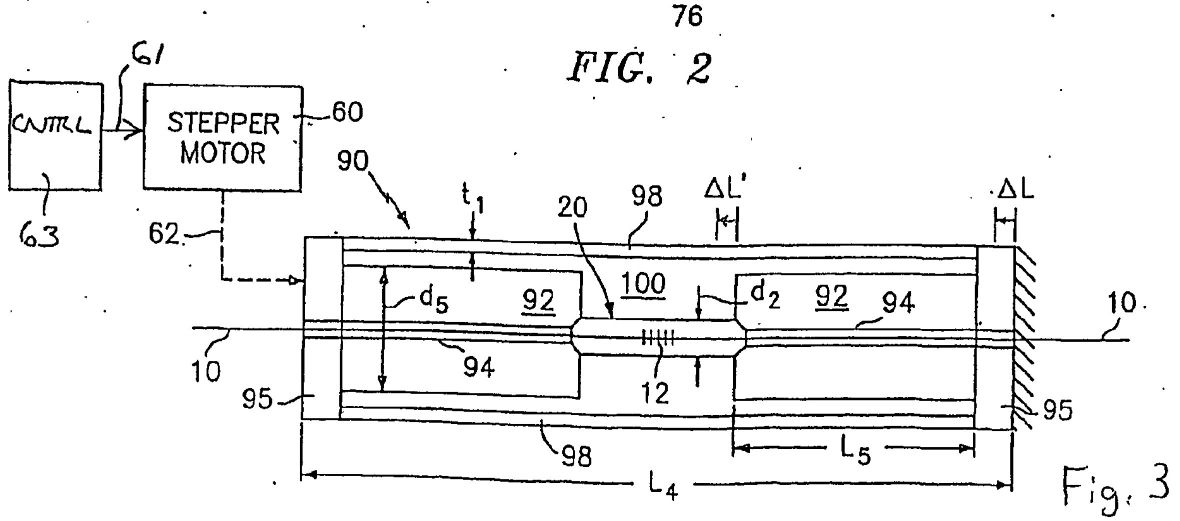


Fig. 3

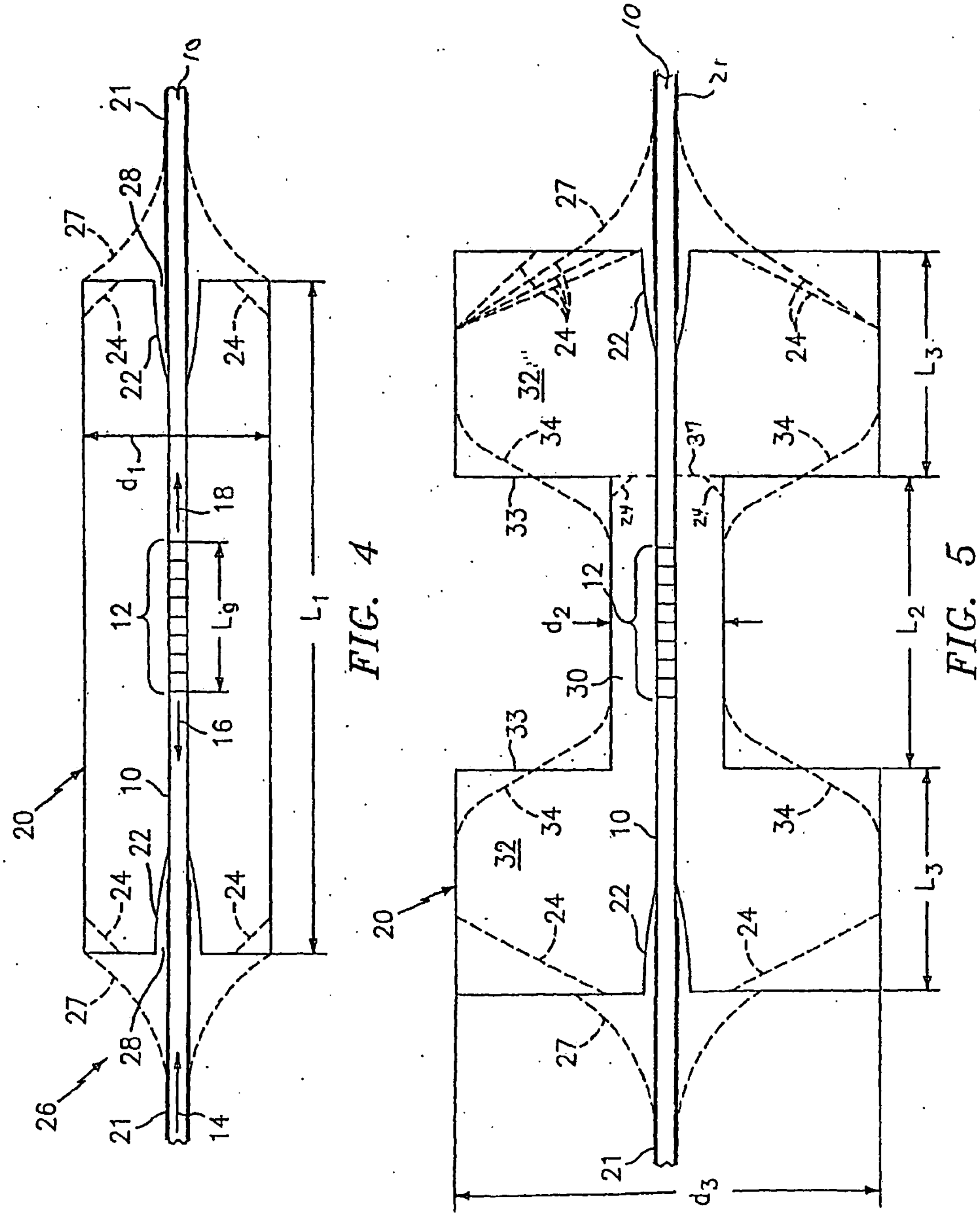


FIG. 4

FIG. 5

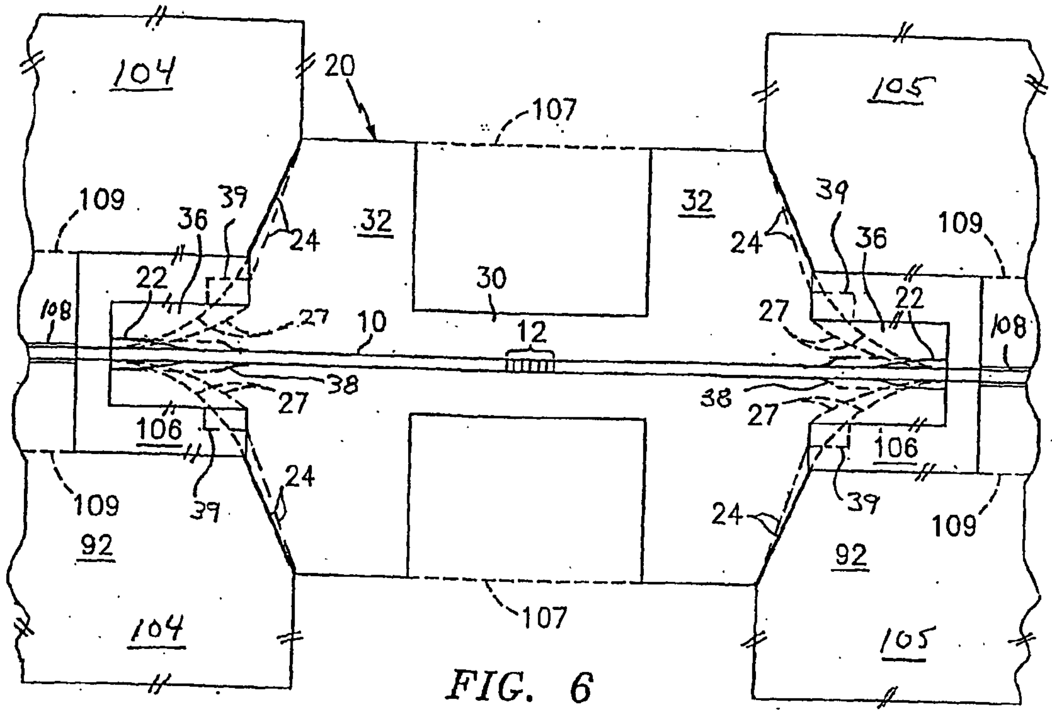


FIG. 6

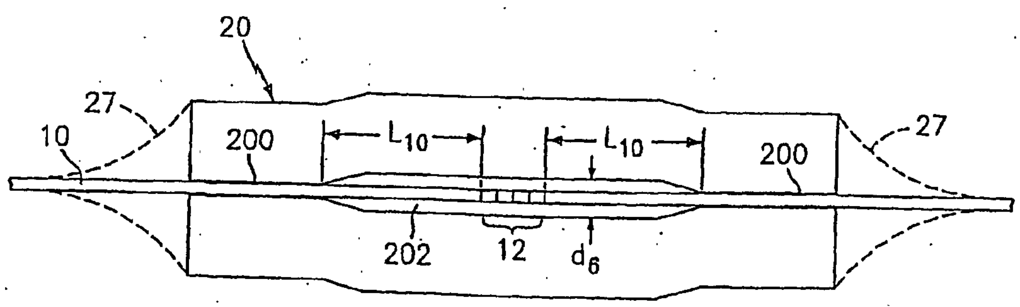


FIG. 7

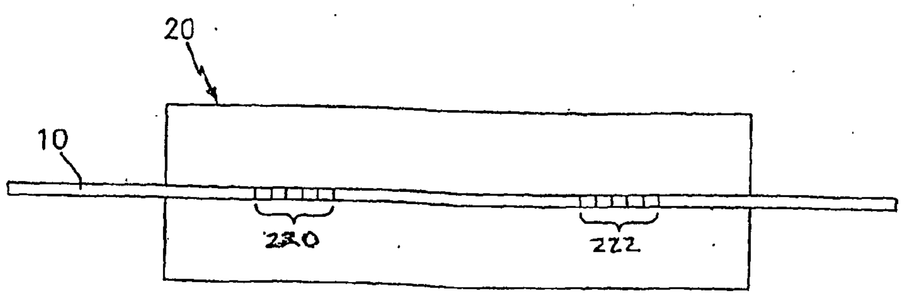


FIG. 8

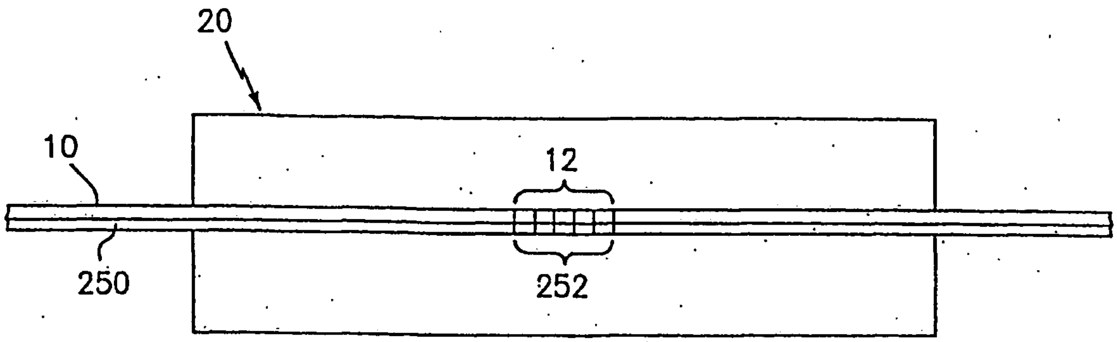


FIG. 9

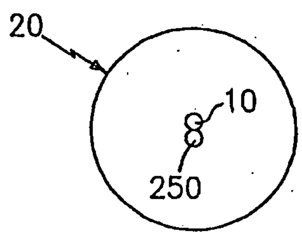


FIG. 10

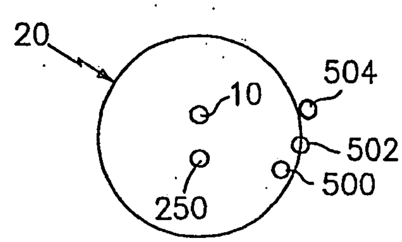


FIG. 11

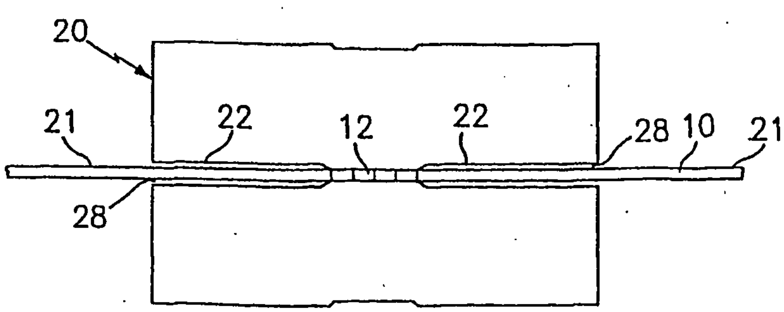


FIG. 12

Fig. 14

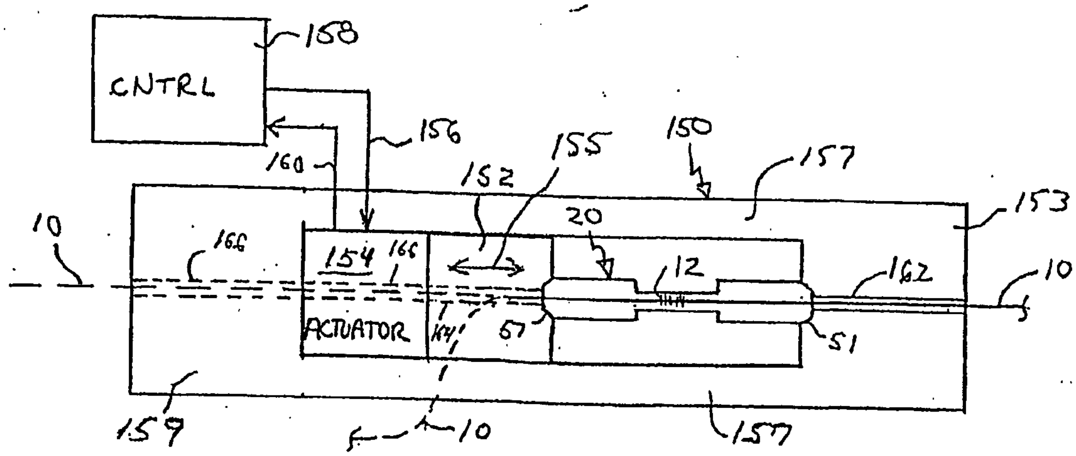


Fig. 15

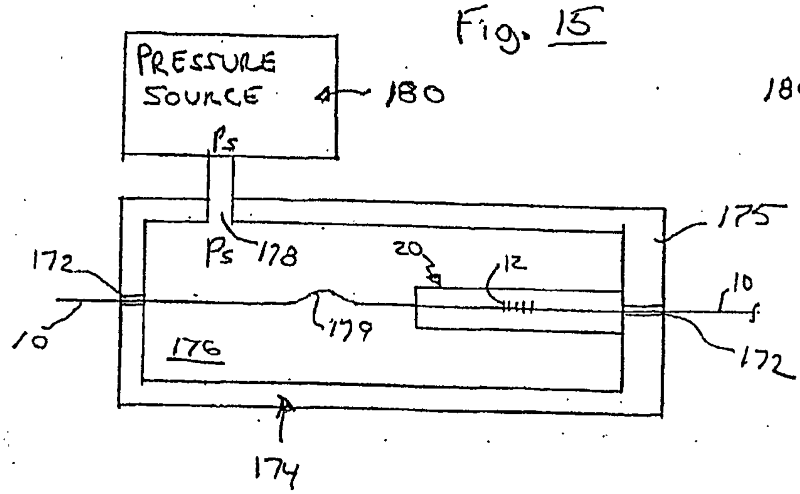


Fig. 16

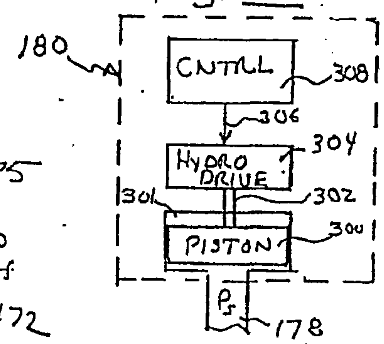


Fig. 13

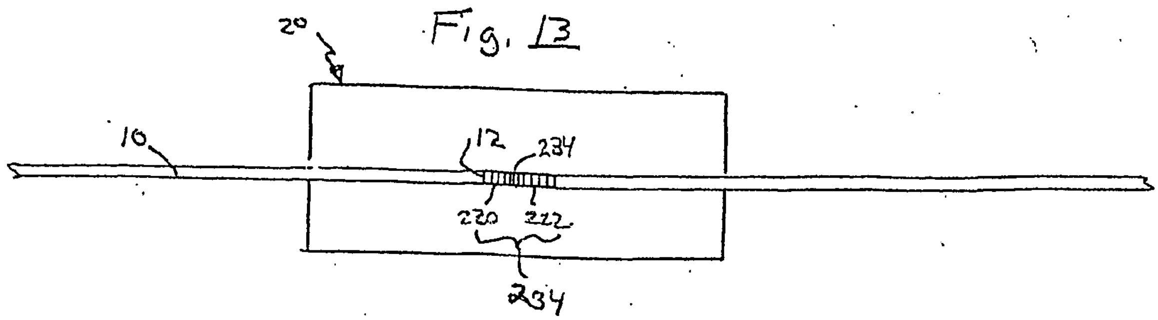
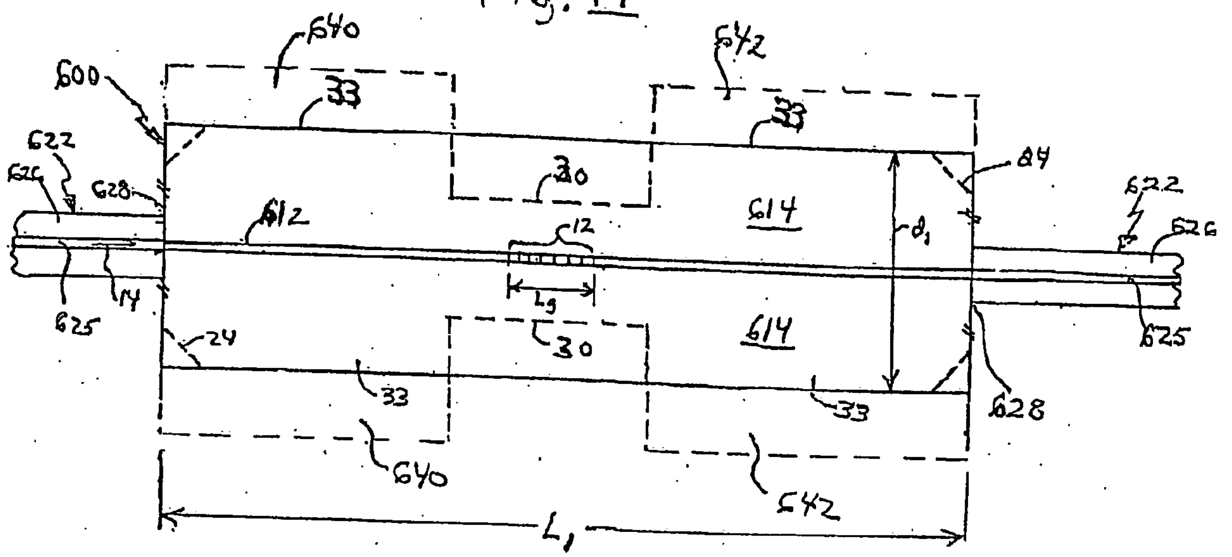


Fig. 17



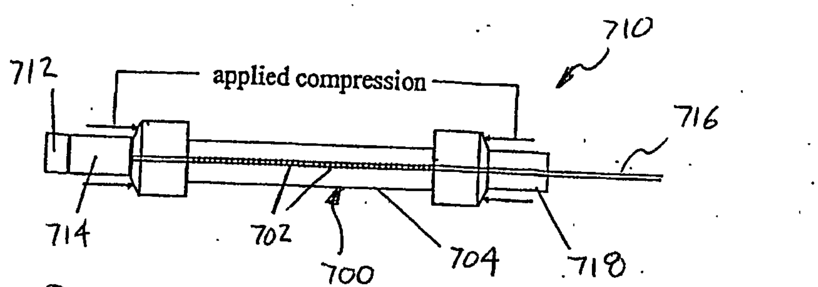


Fig. 18

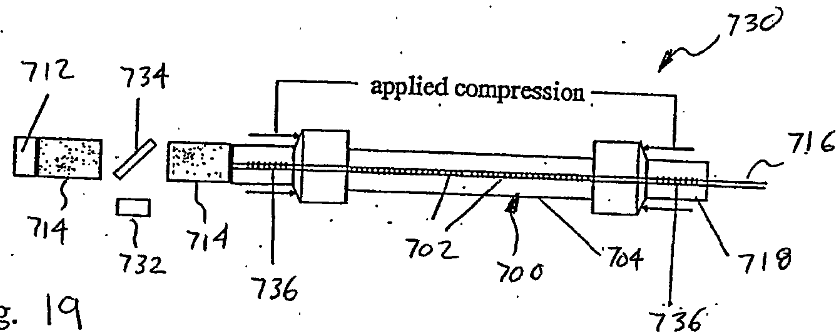


Fig. 19

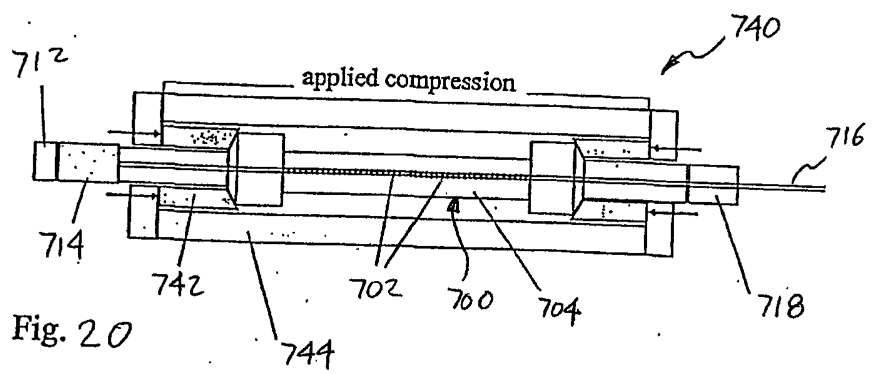


Fig. 20

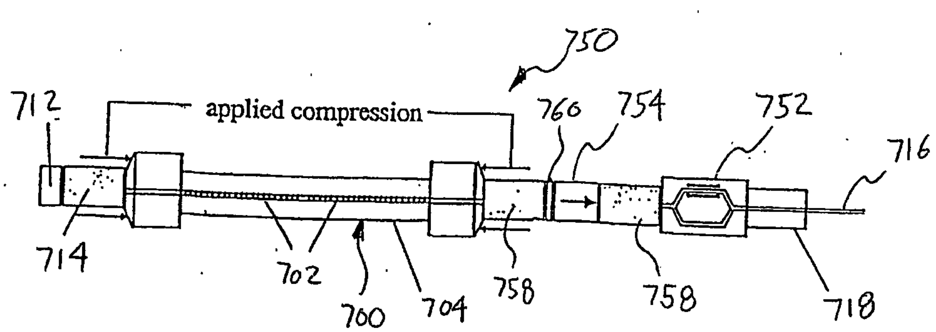
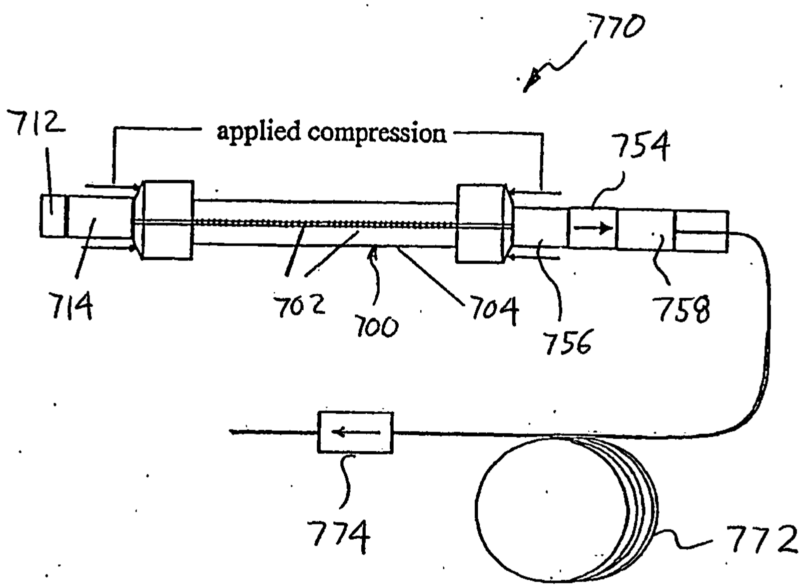


Fig. 21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712
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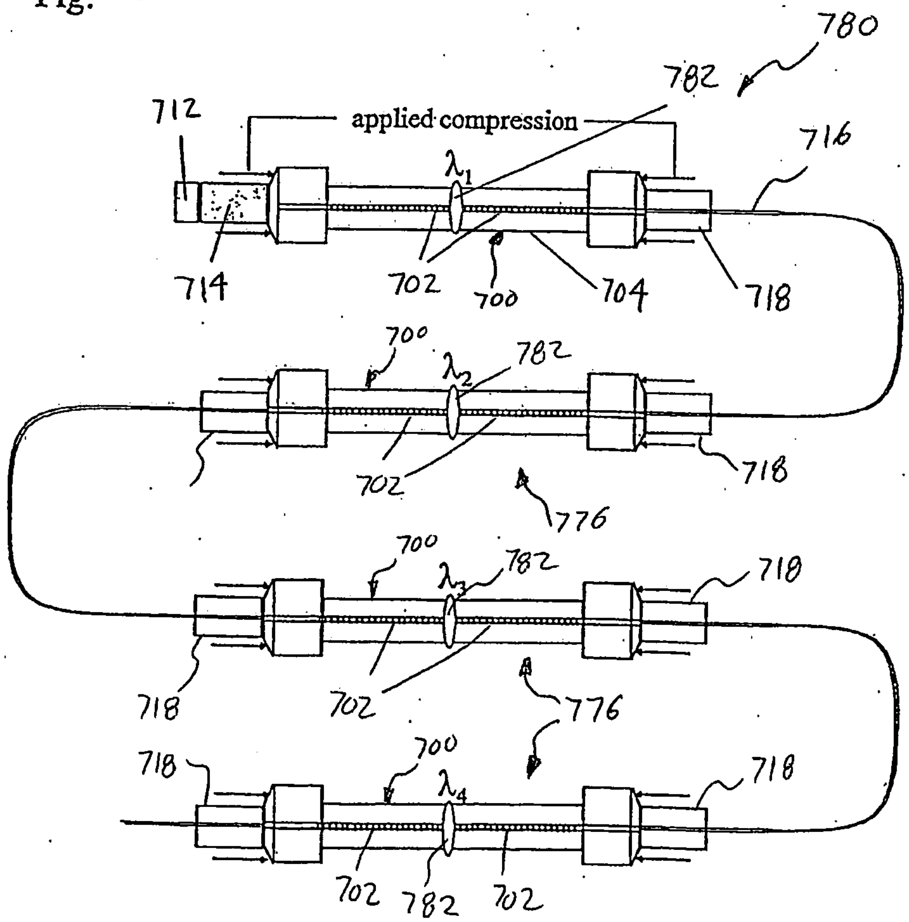
754
714
702
700
704
756
758
774
772

Fig. 22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λ_2
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718
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776
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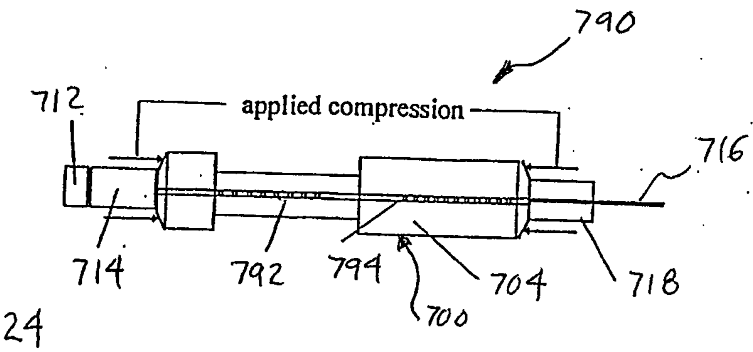
700
718
λ_4
702
782
702

Fig. 23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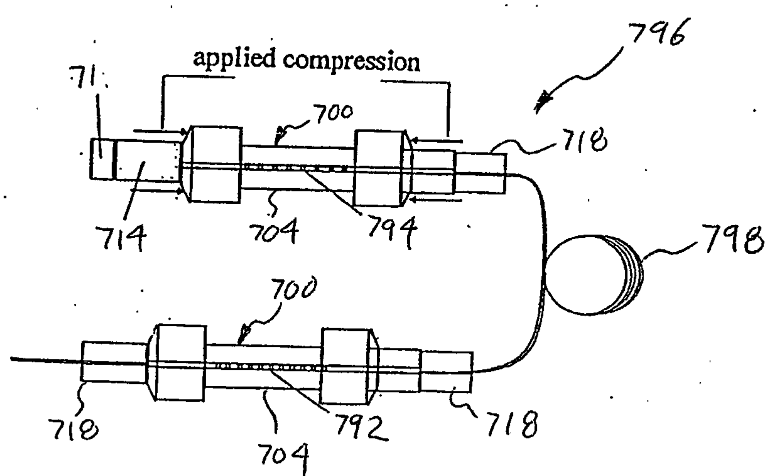
applied compression
712
716
714
792
794
704
718
700

Fig. 24


796
applied compression
71
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718
714
704
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798
700
718
792
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704

Fig. 25

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09/707,084 6 November 2000 (06.11.2000) US

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(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW.

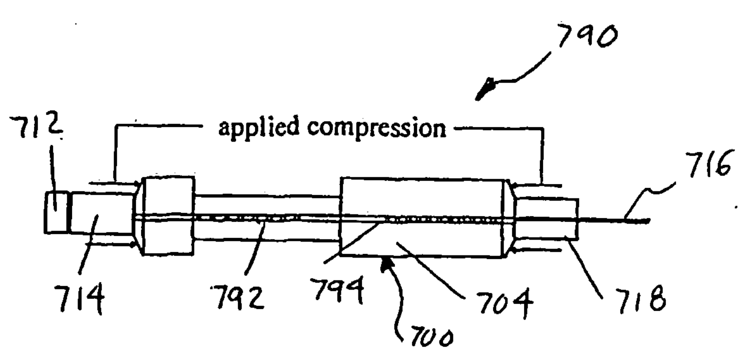
(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

(88) Date of publication of the international search report: 26 September 2002

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: COMPRESSION-TUNED BRAGG GRATING-BASED LASER



(57) Abstract: A compression-tuned bragg grating-based laser includes a tunable optical element 20,600 which includes either an optical fiber 10 having at least one Bragg grating 12 impressed therein encased within and fused to at least a portion of a glass capillary tube 20 or a large diameter waveguide grating 600 having a core and a wide cladding. Light 14 is incident on the grating 12 and light 16 is reflected at a reflection wavelength $\lambda 1$. The tunable element 20,600 is axially compressed which causes a shift in the reflection wavelength of the grating 12 without buckling the element. The shape of the element may be other geometries (e.g., a"dogbone" shape) and(or more than one grating or pair of gratings may be used and more than one fiber 10 or core 612 may be used. At least a portion of the element may be doped between a pair of gratings 150,152, to form a compression-tuned laser or the grating 12 or gratings 150,152 may be constructed as a tunable DFB laser. Also, the element 20 may have an inner tapered region 22 or tapered (or fluted) sections 27. The compression may be done by a PZT, stepper motor, hydraulic device or other actuator.

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 01/47356

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01S3/067 H01S3/1055

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, IBM-TDB, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 691 999 A (BALL GARY A ET AL) 25 November 1997 (1997-11-25) cited in the application column 2, line 66 -column 4, line 51; figure 1 ---	1,9
A	WO 00 37969 A (CIDRA CORP) 29 June 2000 (2000-06-29) page 17, line 6 -page 18, line 8; figures 13-15 ---	1,9
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[X] Further documents are listed in the continuation of box C.

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Date of the actual completion of the international search	Date of mailing of the international search report
31 May 2002	11/06/2002

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Gnugesser, H

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	BALL G A ET AL: "COMPRESSION-TUNED SINGLE-FREQUENCY BRAGG GRATING FIBER LASER" OPTICS LETTERS, OPTICAL SOCIETY OF AMERICA, WASHINGTON, US, vol. 19, no. 23, 1 December 1994 (1994-12-01), pages 1979-1981, XP000484576 ISSN: 0146-9592 the whole document	1,9
A	WO 00 37914 A (CIDRA CORP) 29 June 2000 (2000-06-29) cited in the application page 26, line 14 -page 29, line 23 page 30, line 24 -page 31, line 16; figures 28-30	1,9

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 01/47356

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			WO	0037914	A2	29-06-2000